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Abstract

SIM-France is a large connected atmosphere/land surface/river/groundwater modeling system that simulates the water cycle throughout metropolitan France. The work presented in this study investigates the replacement of the river routing scheme in SIM-France by a river network model called RAPID to enhance the capacity to relate simulated flows to river gages and to take advantage of the automated parameter estimation procedure of RAPID. RAPID was run with SIM-France over a ten-year period and results compared with those of the previous river routing scheme. We found that while the formulation of RAPID enhanced the functionality of SIM-France, the flow simulations are comparable in accuracy to those previously obtained by SIM-France. Sub-basin optimization of RAPID parameters was found to increase model efficiency. A single criterion for quantifying the quality of river flow simulations using several river gages globally in a river network is developed that normalizes the square error of modeled flow to allow equal treatment of all gaging stations regardless of the magnitude of flow. The use of this criterion as the cost function for parameter estimation in RAPID allows better results than by increasing the degree of spatial variability in optimization of model parameters. Likewise, increased spatial variability of RAPID parameters through accounting for topography is shown to enhance model performance.

Keywords stream flow, river network, network matrix, parameters, estimation, dam, quad-tree

1. Introduction

In the past two decades, several large scale river routing schemes have been used along with land surface models for hydrologic modeling. Among the most notable applications of large scale river routing are TRIP [Total Runoff Integrating Pathways, *Ngo-Duc, et al.*, 2007; *Oki and Sud*, 1998], RiTHM [River-Transfer Hydrological Model, *Ducharne, et al.*, 2003], the routing model of Lohmann et al. [*Lohmann, et al.*, 1996; 1998a; 1998b; 1998c; 2004; *Maurer, et al.*, 2001], that of Wetzel [*Abdulla, et al.*, 1996; *Nijssen, et al.*, 1997; *Wetzel*, 1994], and that of Olivera et al. [2000]. These approaches have been used along with land surface parameterization schemes to calculate river flow from runoff at the regional, continental and the global scale. MODCOU [Modèle Couplé, *Ledoux, et al.*, 1989] is another model with routing capabilities that differs from the previously cited models in that it has two separate networks of grid cells for horizontal routing of water on the land surface: one for overland routing and one for routing within the river system. MODCOU simulates flows throughout Metropolitan France (mainland France and Corsica) as part of the SIM-France modeling framework [*Habets, et al.*, 2008]. SIM-France (SAFRAN-ISBA-MODCOU-France) is a large connected atmosphere, land surface, river and groundwater model (see Figure 1) that involves coupling the national-scale atmospheric analysis system SAFRAN [Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige, *Durand, et al.*, 1993; *Quintana-Seguí, et al.*, 2008], with the ISBA land surface model [Interactions Soil- Biosphere-Atmosphere, *Boone, et al.*, 1999; *Noilhan and Planton*, 1989], and with the MODCOU hydrogeological model [*Ledoux, et al.*, 1989]. ISBA computes the vertical water and energy balance between the land surface and the atmosphere. The improved physics of the land surface parameterization of ISBA that consist of an exponential profile for soil hydraulic conductivity developed in Decharme et al. [2006] with calibration of soil hydraulic conductivity and subgrid runoff over France by Quintana-Seguí et al. [2009] are used in this study. Surface runoff and deep-soil drainage are computed by ISBA and transferred to MODCOU which computes the horizontal flow routing on the land surface, in rivers and in aquifers. Aquifers in MODCOU are modeled within the two main river basins of France, the Seine and the Rhône, which together represent 30% of the land area of France.

MODCOU handles the calculations of flow and volume of water within the river network of SIM-France. This river network is made up of grid cells divided into a quad-tree pattern and the calculations of MODCOU are made for groups of quad-tree cells; not for each quad-tree cell separately. Using groups of cells for calculations is advantageous for reducing computational costs but it limits the modularity of MODCOU. In particular, the location and number of gaging stations are difficult to modify.

The work presented herein investigates the impact of replacing the routing module used in MODCOU by a river network model called RAPID [Routing Application for Parallel ComputatIon of Discharge, *David, et al.*, 2011]. RAPID uses a matrix-based version of the Muskingum method to calculate flow and volume of water for each reach of a river network separately and has an automated parameter estimation procedure. RAPID therefore allows greater flexibility than the routing module in MODCOU with regards to changing the locations of computations in an existing domain or to running SIM on a new domain. RAPID was previously applied to a GIS vector river network [*David, et al.*, 2011], and the present study shows how it can also be applied to a quad-tree gridded river network. In addition, RAPID is advantageous because of its ability to run in a parallel computing environment and its fine time step allowing potential comparison with river flow observations at high temporal resolution. Finally, replacing the routing module of MODCOU by RAPID has already allowed computing river flow height and helping quantify river/aquifer interactions at the regional scale [*Saleh, et al.*, 2010; 2011].

In this paper, the original river routing of MODCOU as well as that of RAPID are briefly presented followed by a ten-year application (1995-2005) of SIM-France comparing the two river routing applications for different sets of parameters used in RAPID.

2. Modeling framework

2.1. River modeling in SIM-France

The computational domain of SIM-France includes all of Metropolitan France, including Corsica. Parts of Spain, Switzerland, Germany and Belgium are also included where their drainage area flows through France, as shown in Figure 2. The total surface area of the computational domain is 610,000 km^2.

Surface routing and river routing in SIM-France are done by MODCOU [*Ledoux, et al.*, 1989]. The surface and river networks of SIM-France and their connectivity were created using a routine called HydroDem [*Leblois and Sauquet*, 2000] and consist of 193,861 surface cells and 24,264 river cells, each river cell being a particular surface cell. The surface area covered by the river cells is 65,000 km^2. The surface network uses a quad-tree structure with cell sizes of 1 km, 2 km, 4 km and 8 km. The river network has cell sizes of 1 km and 2 km. The smaller quad-tree cells are used at the conference of branches of the river network for better representation of the network connectivity and at basin boundaries for more accurate basin surface area.

The connectivity between river cells is given by a table that provides for each downstream river cell up to three upstream river cells. There are no loops or divergences in the river network of SIM-France. The connectivity between catchments and rivers is given by a table that provides for each surface cell a unique downstream cell where its runoff enters the river.

For both surface and river routing, the calculations of flow and volume of water within MODCOU are carried out using groups of cells as computing elements, therefore minimizing the amount of calculations compared to computing for all cells separately.

These groups of cells – or isochrone zones – are based on the notion of isochronism developed by Leblanc and Villeneuve [1978]. An isochrone is a line representing a constant time of travel to a reference point downstream. An isochrone zone is the area between two successive isochrones. This zone is represented by a set of cells which are a single computational unit in MODCOU. Both the land surface isochrones and river isochrones of MODCOU have three-hour time intervals, which means that the time of travel between the upstream-most and the downstream-most cell in a given isochrone zone is approximately three hours. All the isochrones of a given network are determined using the travel time between connected cells which is estimated based on topography and on the geometry of the quad-tree mesh. For surface cells and river cells, the travel time $\tau_{i,j}$ between two consecutive cells i and j is calculated using the distance $d_{i,j}$ between the two cells and the slope $s_{i,j}$, as shown in Equation (1):

$$\tau_{i,j} = \alpha \cdot \frac{d_{i,j}}{\sqrt{s_{i,j}}} \tag{1}$$

where α is the inverse of a velocity. In the current version of SIM-France, a unique value of α is calibrated for each major basin.

Figure 3 shows an example of the isochrone zones and connectivity between surface cells and river cells in MODCOU for the Ardèche River Basin. Figure 3a) shows the Ardèche River, its basin and three river gages. Figure 3b) shows the river isochrone zones of the Ardèche River. Figure 3c) shows the surface isochrone zones corresponding to the upstream-most river isochrone zone. Each surface cell belongs to a surface isochrone zone, but only the isochrone zones corresponding to one river isochrone zone are shown of Figure 3c) for clarity. The units used for isochrone zones are the number or MODCOU 3-hour time steps to the outlet (here the Mediterranean). The quad-tree structure of increasing resolution can be seen at the boundary of the basin in Figure 3c).

In MODCOU, the volume of water V^{out} that discharges across each isochrone line in a computation time step is calculated differently for the surface network and for the river network. For routing on the land surface, all the volume of water V available in the isochrone zone is transferred to the downstream zone, as shown in Equation (2):

$$V^{out} = V \tag{2}$$

For routing in the river network, V^{out} is proportional to the volume of water V available within the isochrone zone as shown in Equation (3):

$$V^{out} = \beta \cdot V \tag{3}$$

where $\beta \in [0,1]$ is manually calibrated and usually set constant for large basins. Equation (3) can be viewed as the linear reservoir equation associated with a first-order explicit development of the continuity equation. The variation of volume related to lateral inflow and groundwater inflow of water are added to the volume V before calculating V^{out}. In SIM-France, β has four possible values: 0.5, 0.7, 0.8 and 0.9 as shown in Figure 4.

Equation (3) is applied to isochrone zones. Hence, the volume of water within each isochrone zone needs be partitioned among its several river cells before computation of the river-aquifer exchanges. This interaction depends on the aquifer head, on the river head – assumed constant – and on the volume of water in the river cell when the river infiltrates water into the aquifer. The partitioning of water volume among all cells of an isochrone zone is done using a weighted average of the total amount of water reflecting the spatial distribution of lateral inflow in each isochrone zone.

This formulation has several inconsistencies, especially when the junction between two streams lies in the interior of an isochrone zone. This can have a consequence in river-aquifer interactions, but also in the computation of river flow. Furthermore, using only one set of isochrones in each basin can lead to two gages being located in one isochrone zone (for example a zone containing a confluence with gaging stations on both sides), in which case the flow computed by MODCOU has to match the flow at two different gaging stations. In order to avoid such inconsistencies, MODCOU uses a unique set of isochrone zones for each gage, such that each gage is the downstream-most river cell in its isochrone zone. Therefore, several flow calculations can be performed for a given cell, if the given cell belongs to several isochrone zones, which is inefficient and requires time consuming processing work in case of change of number or locations or river gages.

The work done herein aims at simplifying the river modeling done within SIM-France and to ensure evolution of the code as for instance the computation of river flow height [*Saleh, et al.*, 2010; 2011] and velocity.

2.2. RAPID

RAPID [*David, et al.*, 2011] is a river network model that uses a matrix-based version of the Muskingum routing scheme to calculate discharge simultaneously through a river network. RAPID was first applied to the Guadalupe and San Antonio River Basins in Texas using a vector-based river network extracted from a geographic information system dataset called NHDPlus [*USEPA and USGS*, 2007]. The governing equation used in RAPID is the following:

$$(\mathbf{I}-\mathbf{C_1}\cdot\mathbf{N})\cdot\mathbf{Q}(t+\Delta t)=\mathbf{C_1}\cdot\mathbf{Q^e}(t)+\mathbf{C_2}\cdot\left(\mathbf{N}\cdot\mathbf{Q}(t)+\mathbf{Q^e}(t)\right)+\mathbf{C_3}\cdot\mathbf{Q}(t) \quad (4)$$

where t is time and Δt is the river routing time step. The bolded notation is used for vectors and matrices. All matrices are square. $\mathbf{I}$ is the identity matrix. $\mathbf{N}$ is the river network connectivity matrix which has a value of one in element $N_{i,j}$ if reach j flows into reach i and zero elsewhere. $\mathbf{C_1}$, $\mathbf{C_2}$ and $\mathbf{C_3}$ are parameter matrices which depend on Muskingum k, x and time step Δt. $\mathbf{Q}(t)$ is a vector of outflows from river reaches, and $\mathbf{Q^e}(t)$ is a vector of lateral inflows to these reaches from land surface runoff or groundwater inflow. The number of river quad-tree cells – here 24,264 – is used for dimension of all vectors and matrices, each element of the vectors corresponding to one river cell.

Provided with a vector of lateral inflows $\mathbf{Q^e}(t)$, RAPID calculates the flow and volume of water in all reaches of a river network, therefore allowing coupling of a river network to most land surface models and groundwater models. A different value for the parameters k and x of the Muskingum method can be assigned for each river quad-tree cell, and RAPID uses two vectors $\mathbf{k}$ and $\mathbf{x}$ as input which are used to compute the values of the matrices $\mathbf{C_1}, \mathbf{C_2}$ and $\mathbf{C_3}$. However, before routing with RAPID, horizontal surface and subsurface routing is needed to transport runoff from a land surface cell to its corresponding river cell. In the present study, this surface and subsurface routing is done by MODCOU and RAPID replaces only the river modeling of MODCOU.

The connectivity information that already exists between the river cells in the SIM-France river network is used to create the network connectivity matrix $\mathbf{N}$ needed by RAPID and described in David et al. [2011].

RAPID uses an automated parameter estimation procedure which, given lateral inflow $\mathbf{Q^e}$ everywhere in the river network, and gage measurements at some locations, determines a best set of parameters based on a square error cost function. As in David et al. [2011], the search for optimal vectors of parameters $\mathbf{k}$ and $\mathbf{x}$ is made by determining two multiplying factors λ_k and λ_x such that:

$$\forall j \in [1, 24264] \qquad k_j^\rho = \lambda_k \cdot \frac{L_j}{c^0} \quad , \quad x_j^\rho = \lambda_x \cdot 0.1 \tag{5}$$

where j is the index of a quad-tree river cell, k_j^ρ and x_j^ρ are its Muskingum parameters, L_j is the flow distance within a river cell and $c^0 = 1 km \cdot h^{-1} = 0.28 m \cdot s^{-1}$ is a reference celerity for the flow wave. The parameters k_j^ρ and x_j^ρ are the same developed in David et al. [2011] and are referred to as ρ parameters in the following. In this study, the size of the side of each quad-tree river cell was used as an approximation of its flow distance.

The value of λ_x is bounded by the interval $[0,5]$ since the Muskingum method is stable only for $x \in [0.0, 0.5]$, as shown in Cunge [1969]. The two scalars λ_k and λ_x are determined such that the corresponding vectors $\mathbf{k}$ and $\mathbf{x}$ minimize the value of an optimization criteria, or cost function. At the end of the optimization procedure, one couple (λ_k, λ_x) is determined for a given part of the network. The values of λ_k and λ_x can be determined for the entire study domain, or for sub-basins. If a sub-basin is located downstream of another sub-basin, observations at a gaging station are used to provide the upstream flow. Therefore, the delineation of sub-basins has to be consistent with the location of available gage measurements.

The optimization procedure uses a line-search algorithm called the Nelder-Mead method [*Nelder and Mead*, 1965] to determine the two scalars λ_k and λ_x.

The use of RAPID within SIM-France allows for flow and volume calculation at each river cell and RAPID allows for the ready inclusion of additional river gages to be used for calibration.

3. Application of RAPID in France

3.1. Optimization of RAPID parameters

This section focuses on the optimization of RAPID parameters with various options used for k_j and x_j, for the optimization cost function and for the spatial variability of the optimization. Two formulations are applied for computing k_j and x_j including one formulation taking topography into account, two cost functions are tested, and three different domain decompositions are used for optimization of parameters. In order to simplify the optimization procedure and to ensure its repeatability, the parameter estimation of RAPID was run uncoupled from SIM-France. Lateral and groundwater inflow to the river network were obtained from a simulation using the standard version of SIM-France (without RAPID) augmented with improved physics of the land surface parameterization of ISBA developed in Decharme et al. [2006] and calibrated over France by Quintana-Seguí et al. [2009]. Daily gage measurements from the French HYDRO database [*SCHAPI*, 2008] were used for the parameter estimation as well as for comparison with daily-averaged flow calculations .

The period of interest of the present study is August 1st 1995 to July 31st 2005. However, the parameter estimation was performed using five months of the first winter (November 1st 1995 to March 31st 1996). As part of the first year (1995-1996) was used for calibration, separate statistical results are presented for 1995-1996 and 1995-2005.

RAPID is run using a 30-minute time step and forced with 3-hourly lateral inflow volumes; daily averages of computed discharge are compared with daily observations at gage locations. There are 907 stations within the river network of SIM-France but only

493 of these have daily measurements every day during the first year (August 1st 1995 to July 31st 1996). Amongst the 493 available stations, the best 291 were utilized for optimization of RAPID parameters. The criterion used for the selection of the 291 best stations is a Nash efficiency [*Nash and Sutcliffe*, 1970] better than 0.5 in the existing SIM-France model (without RAPID) over 1995-1996. This selection excludes the gages that are affected either by dams or by water diversions, and thus avoids unrealistic model parameters due to anthropogenic modifications of river flow. Therefore, the proposed routing scheme is optimized at locations were the previous routing scheme already performed well.

The optimization is first performed on all rivers of the domain, therefore obtaining unique values of λ_k and λ_x for all 24,264 river quad-tree cells. However, such an optimization may not capture the variability between river basins and within sub-basins, due to the various slopes or soil types. Therefore, the optimization procedure was also run independently within the seven main river basins of France shown in Figure 5a) and within the twenty sub-basins shown in Figure 5b).

In order to limit the effect of the initial state of the system at the beginning of the optimization procedure, the initial flows on 01 November 1995 were estimated using a simple run of RAPID. This estimation was obtained through running the routing model from 01 August to 31 October 1995 with uniform values of λ_k and λ_x over the study domain and initial flows $0\ \mathrm{m^3/s}$ for all river cells on 01 August 1995.

The results of a parameter estimation procedure depend slightly on the initial guess for the parameters. Therefore, three different sets of initial guesses for λ_k and λ_x were used:

$(\lambda_k, \lambda_x) = (2,3)$, $(\lambda_k, \lambda_x) = (4,1)$ or $(\lambda_k, \lambda_x) = (1,1)$. The numerical values of these three sets have no particular meaning and serve to start the optimization with a different initial value for $\mathbf{k}$ and $\mathbf{x}$. Each set of initial guesses leads to slightly different results for the optimal λ_k and λ_x. Out of the three sets of optimal λ_k and λ_x that are determined for each sub-basin, only the best is kept. This selection is based on the set of parameters that leads to the smallest value of the optimization cost function.

Once the optimization procedure was completed, RAPID was run with SIM-France over a 10-year period, from August 1995 to July 2005. This section focuses on the first year while the next section studies the ten-year run. In order to compare the overall performance of both routing models on the river network, the Nash efficiency and the root mean square error (RMSE) were calculated for each of the 493 gaging stations over 1995-1996. These criteria are sorted and comparisons between the computations of MODCOU and those of RAPID are shown in Figure 6. The two graphs in Figure 6 do not allow comparing both models at each gaging station since the criteria are sorted, but they depict the overall relative performance of both models. Table 1 shows the average Nash efficiencies and RMSEs obtained by the original version of SIM-France and with RAPID using various optimization procedures. During 1995-1996, 382 stations have a positive efficiency using the standard version of SIM-France. The averages presented in Table 1 show the best 382 values for both efficiency and RMSE, but similar patterns are found for all 493 values or the best 291 values.

In its original formulation, the criterion used in the optimization of RAPID is based on a square error cost function ϕ_1. This function is the sum of the square errors between daily measurements $Q_i^g(t)$ and daily-averaged $\overline{Q_i}(t)$ flow computations for several river gaging stations i and for everyday of a given period of time $[t_o, t_f]$, as shown in Equation (6).

$$\phi_1(\mathbf{k},\mathbf{x}) = \sum_{t=t_o}^{t=t_f} \sum_{i=1}^{i=291} \left[\frac{\overline{Q_i}(t) - Q_i^g(t)}{f} \right]^2 \tag{6}$$

where the summation is made daily and at river cells with active gaging stations only. t_o and t_f are respectively the first day and last day used for the calculation of ϕ_1. $i \in [1, 291]$ is the index for gaging stations. The model parameter vectors $\mathbf{k}$ and $\mathbf{x}$ are kept constant within the temporal interval $[t_o, t_f]$, and the cost function is calculated several times with different sets of parameters during the optimization procedure. f is a scalar that allows ϕ_1 to be of the order of magnitude of 10^1 which is helpful for automated optimization procedures. One can notice that, in ϕ_1, a given fractional error (5% error between modeled and measured flow for example) for two stations with different orders of magnitude for river flow influences the cost function differently. A small fractional error on a gaging station with a large flow penalizes the cost function more than the same fractional error on a gaging station with small flow. The Nash efficiency E is highly influenced by the difference between the model computation and the mean average flow, as shown in Equation (7):

$$E = 1 - \frac{\sum_{t=t_o}^{t=t_f} \left[Q_i^g(t) - \overline{Q_i}(t) \right]^2}{\sum_{t=t_o}^{t=t_f} \left[Q_i^g(t) - \left\langle Q_i^g \right\rangle \right]^2} \tag{7}$$

where $\left\langle Q_i^g \right\rangle$ is the average daily flow observed at the gaging station i over a long interval. Therefore, the use of ϕ_1 penalizes the Nash efficiency. In order to avoid that the order of magnitude of flow at each gaging station influences their weight in the cost function, a new cost function ϕ_2 is created, as shown in Equation (8):

$$\phi_2(\mathbf{k}, \mathbf{x}) = \sum_{t=t_o}^{t=t_f} \sum_{i=1}^{i=291} \left[\frac{\overline{Q_i}(t) - Q_i^g(t)}{\left\langle Q_i^g \right\rangle} \right]^2 \tag{8}$$

The new cost function ϕ_2 results in the changes shown in Table 1 and Figure 6 where the Nash efficiencies and RMSEs obtained with RAPID using ϕ_2 are better than with ϕ_1. Overall, the Nash efficiencies and the RMSEs in RAPID are comparable while not as good as those obtained with the routing scheme of the original SIM-France. Therefore, the choice of the cost function is crucial to determining a set of optimal parameters.

In order to estimate the effect of more spatial variability in the optimization of RAPID parameters, the parameter estimation was done on different basins and sub-basins. Figure 7 shows the sorted Nash efficiencies and RMSEs obtained with three degrees of spatial variability of optimization using ϕ_2 as the cost function. These spatial variabilities include “France” which has uniform parameters over the whole domain, “basins” for the 7 river basins of Figure 5a) (Adour, Garonne, Loire, Seine, Meuse, Rhône and Hérault) and “sub-basins” where the major river basins have been divided into 20 sub-basins as shown in Figure 5b). The increase in spatial variability of optimization increases the efficiency while the RMSE remains almost constant, but the increase in efficiency is limited compared to that triggered by a change in the cost function. The values of parameters λ_k and λ_x obtained with the parameter estimation procedure using the second cost function are shown in Table 2.

The number of gaging stations in a basin can be divided by the number or river cells in the basin to calculate an observability ratio O, as done in Table 2. This ratio ranges from $O = 22$ on the Ardèche River to $O = 1307$ downstream of the Seine River, showing a wide spread in density of observations. The Seine River, of great interest to the French community, has a higher resolution and therefore more river cells in SIM-France than any other basin – all the river cells are of size 1 km – which explains the lower observability ratio. Unrealistically low results are obtained for λ_k in the downstream part of the Seine River and for the Ardèche River Basin. The former is explained by the limited amount of stations used for optimization in the downstream part of the Seine River Basin (only one station). The latter is due to the basin being small with regards to the number of gages (leading to a low observability ratio) and therefore over-constraining the optimization procedure. The observability ratio is therefore a key metric for the quality of the optimization. These unrealistic values for λ_k may partly explain why the effect of optimization from 7 basins to 20 sub-basins is very limited. As expected, the optimization procedure converges to the largest values of the parameter λ_k for the Seine and Loire rivers which are the slowest rivers. For each of the 7 major basins, the value of λ_k is bounded by the value of λ_k for each of their corresponding sub-basins. Also, one can notice that upstream parts of a basin are usually faster (lower λ_k) than downstream parts as can be seen for the upstream part of the Loire Basin, and for the Allier Basin which are located in high topography areas. This shows that – as expected – topography plays an important role in the travel time of flow waves. This motivates a final experiment where RAPID model parameters are estimated based on topography as shown in Equation (9).

$$\forall j \in [1, 24264] \qquad k_j^\sigma = \lambda_k \cdot \alpha \cdot \frac{d_{i,j}}{\sqrt{s_{i,j}}} \quad , \quad x_j^\sigma = \lambda_x \cdot 0.1 \tag{9}$$

This formulation of k_j^σ is adapted from Equation (1) which is used to determine the location of isochrone zones. In the following, the parameters k_j^σ and x_j^σ of Equation (9) are referred to as σ parameters. Table 1 shows the average efficiencies and RMSEs obtained with σ parameters using ϕ_1 and ϕ_2 uniformly over France, and with

σ parameters over the 7 major basins using ϕ_2. Figure 8 shows the sorted efficiencies and RMSEs obtained with σ parameters using ϕ_1 and ϕ_2 uniformly over France. From Table 1 and Figure 8 one can conclude that regardless of the optimization cost function used, σ parameters allow to obtain better results than ρ parameters. Therefore, taking topography into account in the travel time of the flow wave is advantageous. Similarly, regardless of the parameters used and of the spatial resolution of the optimization, optimizing using ϕ_2 allows obtaining better average results than with ϕ_1. The average results obtained using σ parameters and ϕ_2 are comparable (slightly better) than those obtained by the original routing module of SIM-France. One should note however, that the best stations with MODCOU are better than the best with RAPID, while the worse stations in MODCOU are worse than the worst in RAPID. This suggests a flattening of the curves most likely due to equal treatment of all stations in the ϕ_2 cost function. Finally, regardless of the cost function used in optimization or the set of parameters (σ and ρ) basin and sub-basin optimizations have a limited effect on overall performance of RAPID. This suggests that increased inter-basin and intra-basin variability of river routing parameters has little effect on efficiency or RMSE at the spatial scale of France as it is modeled in SIM-France.

3.2. Comparison of routing schemes over 10 years

Over 1995-2005, only 3 gaging stations have a full daily record. Therefore, results presented in this section are using stations with gaps in observations; efficiency and RMSE are calculated only at times when measurements are available. A threshold of 70% of daily measurements available over 1995-2005 leads to selecting 493 gaging stations. These stations differ slightly from the ones used in 1995-1996. Out of the 493 stations that have full daily record in 1995-1996, 436 stations are included in the 1995-2005 period. Similarly, out of the best 291 stations that have full daily record in 1995-1996, 261 are included in 1995-2005. During 1995-2005, 427 out of the 493 stations have a positive efficiency using the standard version of SIM-France. Table 1 shows average statistics for 1995-2005 for the best 427 values for both efficiency and RMSE, but similar patterns are found for all 493 values. The conclusions drawn in Section 3.2. regarding the sets of parameters, the cost functions and the spatial resolution of the optimization are still valid for the ten-year simulation. However, one should note that over ten years, MODCOU performs slightly better than RAPID using the best set of options. This may be explained by the slightly different stations used for the 5-month optimization and for the ten-year study. However, five months of the first year seem to be sufficient to capture RAPID parameters and allow comparable performance between MODCOU and RAPID over ten years. Figure 9 shows the sorted efficiencies and RMSEs obtained with MODCOU and with RAPID with σ parameters optimized uniformly over France using ϕ_2. Globally the two models perform comparably although, similarly to 1995-1996 results, the best stations are degraded and some stations with low but positive efficiency are improved. Figure 10 shows observations and modeled hydrographs during 1995-1996 and 1995-2005 for the Meuse River at Stenay (the location of this station is shown in Figure 11) in which MODCOU and RAPID are almost indiscernible. One should note, however, that in all the hydrographs plotted (not shown) the timing of events differs slightly between the two models, none of which being consistently better than the other regardless of the optimization options as expected from results shown in Table 1 and Figure 9.

Figure 11 shows a spatial comparison of efficiencies obtained over France. Improvements and degradations of statistical results between MODCOU and RAPID have no particular spatial patterns. Overall, the discharge simulated by MODCOU and RAPID are similar in RMSE and Nash efficiency. This similarity can be explained by the strong dependence of discharge calculations on the lateral inflow forcing which is the same for both river routing schemes. Furthermore, the routing equations used in MODCOU and RAPID are comparable (the linear reservoir equation in SIM-France is a simplified Muskingum equation, given x=0). The addition of RAPID to SIM-France can be regarded as advantageous since RAPID provides with flow and volume of water in all the cells of the river network separately and provides flexibility in the number and location of river gages, which was not the case in the original version of SIM-France. Also, the 30-min time step in RAPID allows potential comparisons with observations at higher temporal resolution than the 3-hour time step of MODCOU. Finally, RAPID is better suited than MODCOU for computation of river flow height in all grid cells of the river network separately hence allowing the study of river-aquifer exchanges as shown in Saleh et al. [2010; 2011].

3.3. Influence of dams on river flow

RAPID does not have a specific physical model for treatment of dams. However, the model is designed such that observations at gaging stations can easily be substituted for upstream flow. This capability is not available in the routing scheme of MODCOU and is useful for a gaging station located at the outlet of a dam because the flows discharging from man-made infrastructures reflect human decisions. In France, the quality of flow calculations at the outlet of the Rhône River (at Beaucaire) is influenced by the dam at the outlet of Lake Geneva. Figure 12 demonstrates the influence of forcing with observations at Pougny (downstream of the dam) on the calculation of flow at the outlet of the Rhône River Basin. The gaging station a Pougny is the outlet of the “Rhône upstream” basin in Figure 5b) and is also shown on Figure 11. The first year (August 1st 1995 – July 31st 1996) was used for this experiment. Forcing with observations at Lake Geneva increases the Nash Efficiency from 0.49 to 0.62 at Beaucaire, the outlet of the Rhône basin.

4. Conclusions

The river routing in SIM-France is done by MODCOU which uses groups of cells called isochrone zones for its computations and does not directly compute flow and volume of water for each cell of its quad-tree river network. The use of isochrones limits the flexibility in the number and location of river gages. The work in this paper presents the replacement of the river routing module in MODCOU by the river network model called RAPID. Information on the network connectivity between the quad-tree river cells of SIM-France is readily available in tables that relate upstream and downstream cells. These tables can be used directly to create the network matrix of RAPID. A ten-year study of river flow in Metropolitan France is presented comparing RAPID and the routing module of MODCOU. An automated procedure for determining optimal model parameters is available in RAPID and various options for the estimation of the parameters are investigated. Sub-basin optimization increases model performance but its influence is much smaller than the choice of the cost function. A cost function was developed that normalizes the square-error between observations at each river gage and RAPID computations by the average flow at the gage. This cost function is found to globally increase the Nash efficiency of computed flow in all gages. We suggest that this is due to the average flow having an influence on the computation of the Nash efficiency. Therefore, the use of an appropriate criterion for quantifying the quality of river flow as the cost function for the optimization procedure helps the betterment of model computations. Also, flow wave celerities included in the temporal parameter of the Muskingum method benefit from taking into account topography when compared to a simple constant celerity formulation. Overall, the computation obtained with the addition of RAPID are comparable to those of the original river routing module in SIM-France. We consider the addition of RAPID as advantageous since flow and volume of water is directly computed for each cell of the quad-tree river network. The formulation of RAPID allows for easily substituting observed flows for the upstream calculated flow, which is advantageous when considering a man-made infrastructure as was shown for the Rhône River.

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References

Abdulla, F. A., D. P. Lettenmaier, E. F. Wood, and J. A. Smith (1996), Application of a macroscale hydrologic model to estimate the water balance of the Arkansas Red River basin, *Journal of Geophysical Research-Atmospheres*, *101*, 7449-7459.

Boone, A., J.-C. Calvet, J. Noilhan, and euml (1999), Inclusion of a Third Soil Layer in a Land Surface Scheme Using the Force-Restore Method, *Journal of Applied Meteorology*, *38*, 1611-1630.

Cunge, J. A. (1969), On the subject of a flood propagation computation method (Muskingum method), *Journal of Hydraulic Research*, *7*, 205-230.

David, C. H., D. R. Maidment, G.-Y. Niu, Z.-L. Yang, F. Habets, and V. Eijkhout (2011), River network routing on the NHDPlus dataset, *Journal of Hydrometeorology*, *tentatively accepted on 18 January 2011*.

Decharme, B., H. Douville, A. Boone, F. Habets, and J. Noilhan (2006), Impact of an Exponential Profile of Saturated Hydraulic Conductivity within the ISBA LSM: Simulations over the RhÃ´ne Basin, *Journal of Hydrometeorology*, *7*, 61-80.

Ducharne, A., C. Golaz, E. Leblois, K. Laval, J. Polcher, E. Ledoux, and G. de Marsily (2003), Development of a high resolution runoff routing model, calibration and application to assess runoff from the LMD GCM, *Journal of Hydrology*, *280*, 207-228.

Durand, Y., E. Brun, L. Mérindol, G. Guyomarc'h, B. Lesaffre, and E. Martin (1993), A meteorogical estimation of relevant parameters for snow models, *Annals of Glaciology*, *18*, 65-71.

Habets, F., A. Boone, J. L. Champeaux, P. Etchevers, L. Franchisteguy, E. Leblois, E. Ledoux, P. Le Moigne, E. Martin, S. Morel, J. Noilhan, P. Q. Segui, F. Rousset-

Regimbeau, and P. Viennot (2008), The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France, *Journal of Geophysical Research-Atmospheres*, *113*.

Leblanc, D., and J. P. Villeneuve (1978), Algorithme de schématisation des écoulements d'un bassin versant 1-55 pp, Institut national de la recherche scientifique, Québec.

Leblois, E., and E. Sauquet (2000), Grid elevation models in hydrology. Part 2: HydroDem technical note, 80 pp, Cemagref, Lyon.

Ledoux, E., G. Girard, G. de Marsily, J. P. Villeneuve, and J. Deschenes (1989), Spatially Distributed Modeling: Conceptual Approach, Coupling Surface Water and Groundwater, in *Unsaturated Flow in Hydrologic Modeling Theory and Practice*, edited by H. J. Morel-Seytoux, pp. 435-454, Kluwer Academic Publishers.

Lohmann, D., R. NolteHolube, and E. Raschke (1996), A large-scale horizontal routing model to be coupled to land surface parametrization schemes, *Tellus Series a-Dynamic Meteorology and Oceanography*, *48*, 708-721.

Lohmann, D., D. P. Lettenmaier, X. Liang, E. F. Wood, A. Boone, S. Chang, F. Chen, Y. J. Dai, C. Desborough, R. E. Dickinson, Q. Y. Duan, M. Ek, Y. M. Gusev, F. Habets, P. Irannejad, R. Koster, K. E. Mitchell, O. N. Nasonova, J. Noilhan, J. Schaake, A. Schlosser, Y. P. Shao, A. B. Shmakin, D. Verseghy, K. Warrach, P. Wetzel, Y. K. Xue, Z. L. Yang, and Q. C. Zeng (1998a), The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) phase 2(c) Red-Arkansas River basin experiment: 3. Spatial and temporal analysis of water fluxes, *Global and Planetary Change*, *19*, 161-179.

Lohmann, D., E. Raschke, B. Nijssen, and D. P. Lettenmaier (1998b), Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, *43*, 131-141.

Lohmann, D., E. Raschke, B. Nijssen, and D. P. Lettenmaier (1998c), Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany, *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, *43*, 143-158.

Lohmann, D., K. E. Mitchell, P. R. Houser, E. F. Wood, J. C. Schaake, A. Robock, B. A. Cosgrove, J. Sheffield, Q. Y. Duan, L. F. Luo, R. W. Higgins, R. T. Pinker, and J. D. Tarpley (2004), Streamflow and water balance intercomparisons of four land surface models in the North American Land Data Assimilation System project, *Journal of Geophysical Research-Atmospheres*, *109*, 1-22.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001), Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE reanalyses using an off-line hydrologic model, *Journal of Geophysical Research-Atmospheres*, *106*, 17841-17862.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models part I -- A discussion of principles, *Journal of Hydrology*, *10*, 282-290.

Nelder, J. A., and R. Mead (1965), A Simplex Method for Function Minimization, *The Computer Journal*, *7*, 308-313.

Ngo-Duc, T., T. Oki, and S. Kanae (2007), A variable streamflow velocity method for global river routing model: model description and preliminary results, *Hydrol. Earth Syst. Sci. Discuss.*, *4*, 4389-4414.

Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E. F. Wood (1997), Streamflow simulation for continental-scale river basins, *Water Resources Research*, *33*, 711-724.

Noilhan, J., and S. Planton (1989), A Simple Parameterization of Land Surface Processes for Meteorological Models, *Monthly Weather Review*, *117*, 536-549.

Oki, T., and Y. C. Sud (1998), Design of Total Runoff Integrating Pathways (TRIP) - A Global River Channel Network, *Earth Interactions*, *2*, 1-35.

Olivera, F., J. Famiglietti, and K. Asante (2000), Global-scale flow routing using a source-to-sink algorithm, *Water Resources Research*, *36*, 2197-2207.

Quintana-Seguí, P., P. Le Moigne, Y. Durand, E. Martin, F. Habets, M. Baillon, C. Canellas, L. Franchisteguy, and S. Morel (2008), Analysis of near-surface atmospheric variables: Validation of the SAFRAN analysis over France, *Journal of Applied Meteorology and Climatology*, *47*, 92-107.

Quintana-Seguí, P., E. Martin, F. Habets, and J. Noilhan (2009), Improvement, calibration and validation of a distributed hydrological model over France, *Hydrol. Earth Syst. Sci.*, *13*, 163-181.

Saleh, F. S. M., N. Flipo, F. Habets, A. Ducharne, L. Oudin, M. Poulin, P. Viennot, and E. Ledoux (2010), CONTRIBUTION OF 1D RIVER FLOW MODELING TO THE QUANTIFICATION OF STREAM-AQUIFER INTERACTIONS IN A REGIONAL HYDROLOGICAL MODEL, paper presented at XVIII International Conference on Computational Methods in Water Resources (CMWR 2010) CMWR 2010, Barcelona.

Saleh, F. S. M., N. Flipo, F. Habets, A. Ducharne, L. Oudin, P. Viennot, and E. Ledoux (2011), Modeling the impact of in-stream water level fluctuations on stream-aquifer interactions at the regional scale, *Journal of Hydrology*, *accepted*.

SCHAPI (2008), Banque HYDRO, Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations available online at http://www.hydro.eaufrance.fr/index.php.

USEPA, and USGS (2007), NHDPlus User Guide, available online at http://www.horizon-systems.com/nhdplus/documentation.php.

Wetzel, S. (1994), A hydrological model for predicting the effects of climate change, 85 pp, Princeton University, Princeton.

Table 1 Average efficiencies and average root mean square errors computed for MODCOU and for RAPID with 7 different sets of parameters. The best 382 values are used for 1995-1996 and the best 427 values are used for 1995-2005.

				1995-1996		1995-2005	
				Best 382 values		Best 427 values	
Vector of parameters used in optimization	Optimization cost function	Spatial optimization	Model	Average efficiency	Average RMSE (m^3/s)	Average efficiency	Average RMSE (m^3/s)
N/A	N/A	N/A	MODCOU	0.617	8.37	0.650	12.67
ρ	ϕ_1	France	RAPID	0.581	8.85	0.614	13.64
ρ	ϕ_2	France	RAPID	0.611	8.39	0.638	13.07
ρ	ϕ_2	7 basins	RAPID	0.615	8.40	0.640	13.06
ρ	ϕ_2	20 sub-basins	RAPID	0.615	8.38	0.637	13.04
σ	ϕ_1	France	RAPID	0.602	8.63	0.632	13.25
σ	ϕ_2	France	RAPID	0.620	8.37	0.647	12.91
σ	ϕ_2	7 basins	RAPID	0.624	8.32	0.646	12.92

Table 2 Results of optimization procedure using ρ parameters and the ϕ_2 cost function

Basin	Sub-basin	Number of river cells	Number of stations	Observa-bility ratio	Optimized λ_k	Optimized λ_x	Basin	Sub-basin	Number of river cells	Number of stations	Observa-bility ratio	Optimized λ_k	Optimized λ_x
France	all basin	24264	291	83.4	0.366	0.237	Loire	Loire downstream	1763	25	70.5	0.436	0.091
Adour	all basin	666	9	74.0	0.375	0.313	Seine	all basin	5115	41	124.8	0.531	0.234
Garonne	all basin	2985	58	51.5	0.294	0.009	Seine	Seine upstream	2919	30	97.3	0.579	0.145
Garonne	Garonne upstream	558	5	111.6	0.160	0.420	Seine	Oise	889	10	88.9	0.469	3.766
Garonne	Tarn	356	8	44.5	0.152	0.674	Seine	Seine downstream	1307	1	1307.0	0.031	4.984
Garonne	Lot	369	10	36.9	0.394	0.113	Meuse	all basin	832	3	277.3	0.383	0.059
Garonne	Dordogne	431	12	35.9	0.356	0.056	Rhône	all basin	3426	51	67.2	0.256	0.118
Garonne	Garonne downstream	1271	23	55.3	0.375	0.313	Rhône	Saône	1043	32	32.6	0.236	0.007
Loire	all basin	4138	88	47.0	0.414	0.197	Rhône	Ardèche	66	3	22.0	0.000	0.156
Loire	Vienne	706	20	35.3	0.386	0.145	Rhône	Rhône upstream	279	1	279.0	0.500	4.750
Loire	Allier	458	17	26.9	0.308	2.670	Rhône	Rhône downstream	2038	15	135.9	0.403	0.076
Loire	Loire upstream	541	12	45.1	0.391	0.305	Hérault	Hérault	101	3	33.7	0.375	4.813
Loire	Loir	670	14	47.9	0.453	0.273							

Captions to illustrations

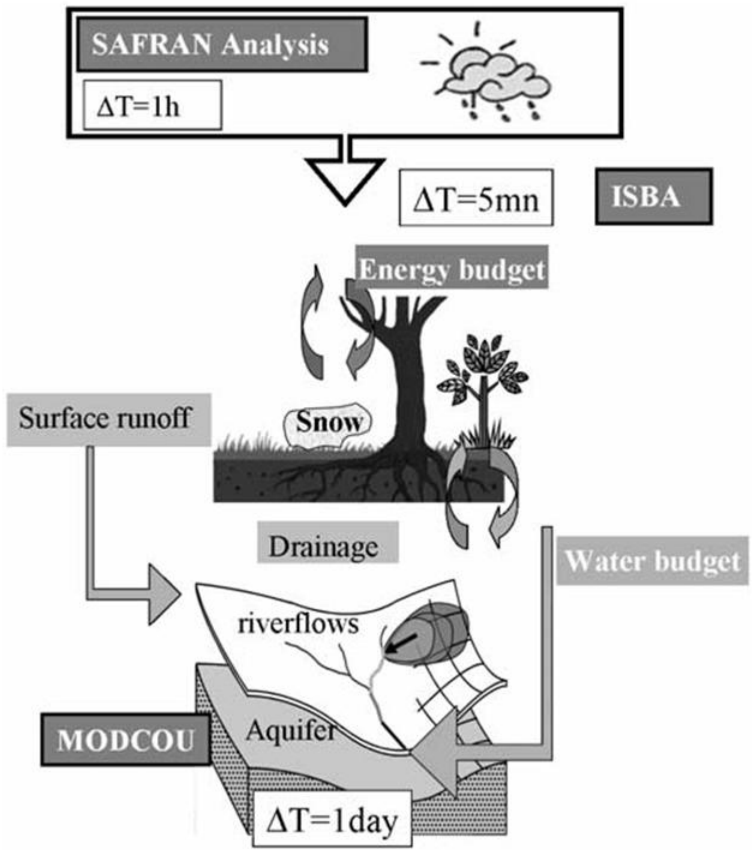

Figure 1 Structure of SIM-France, from Habets et al. [2008]

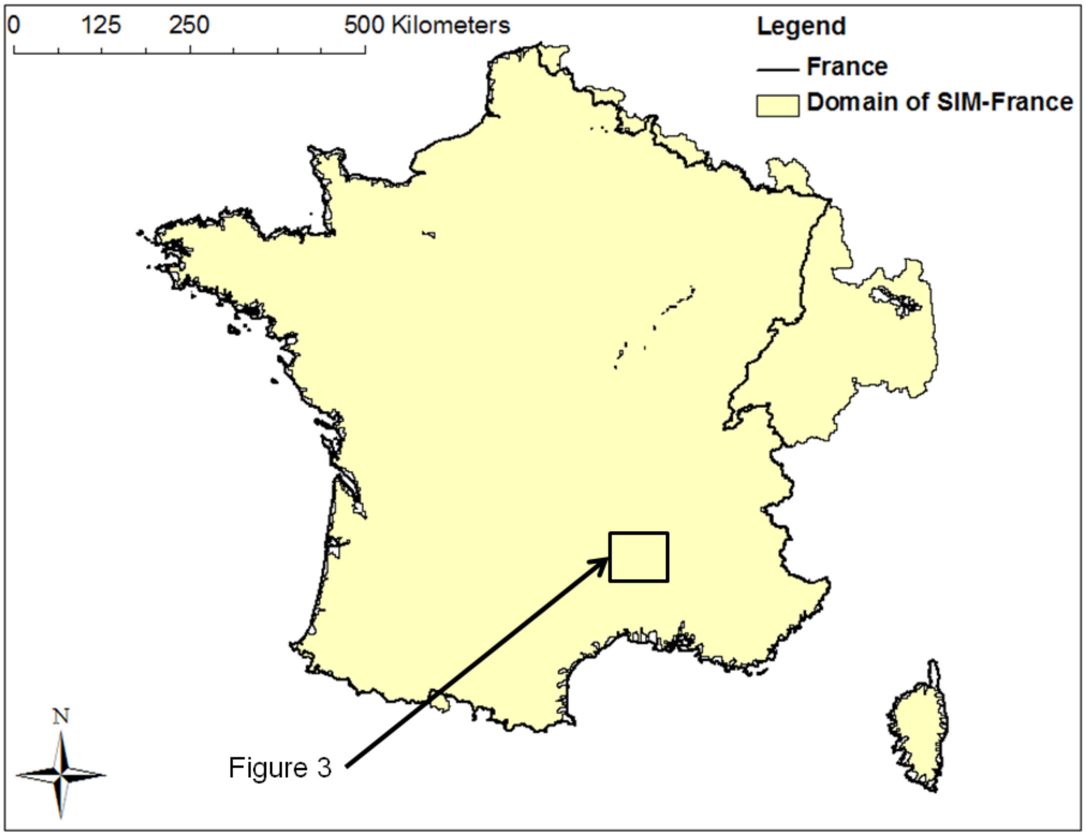

Figure 2 France and computational domain of SIM-France

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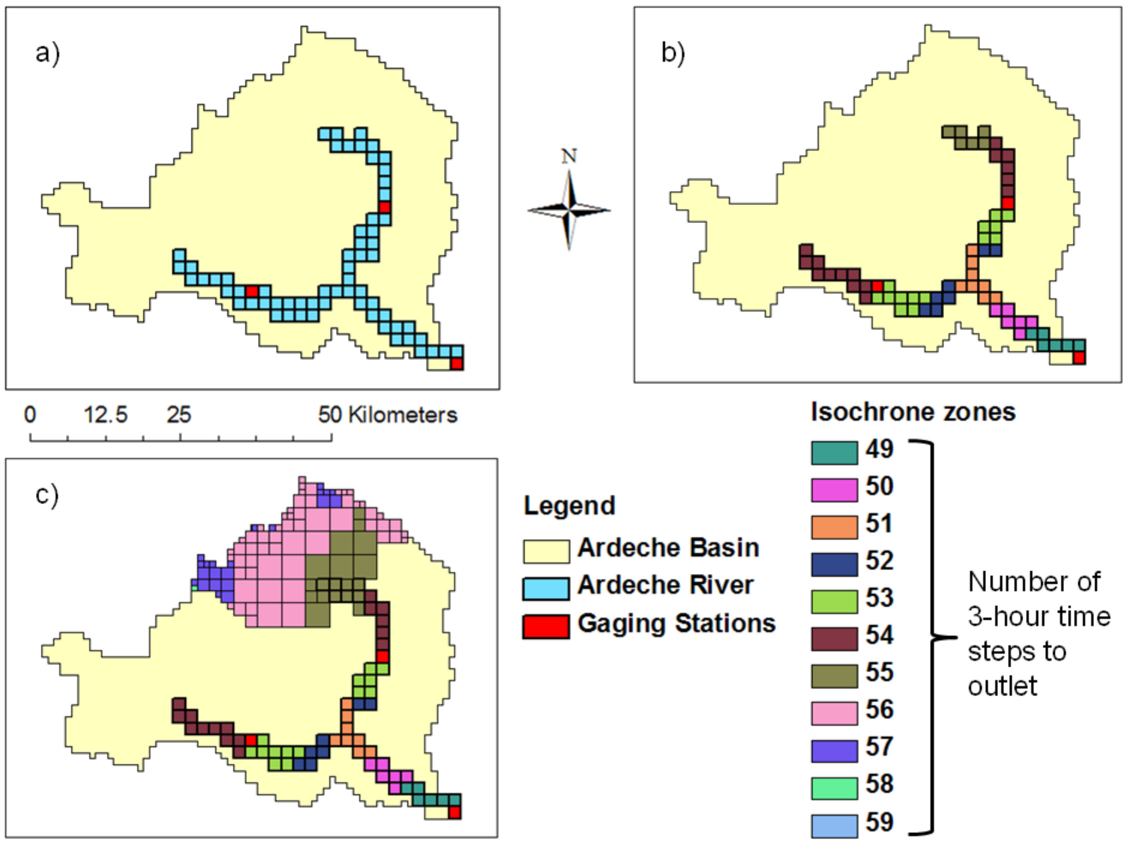

626 Figure 3 Surface and river isochrone zones in Ardèche Basin in MODCOU within

627 SIM-France

628

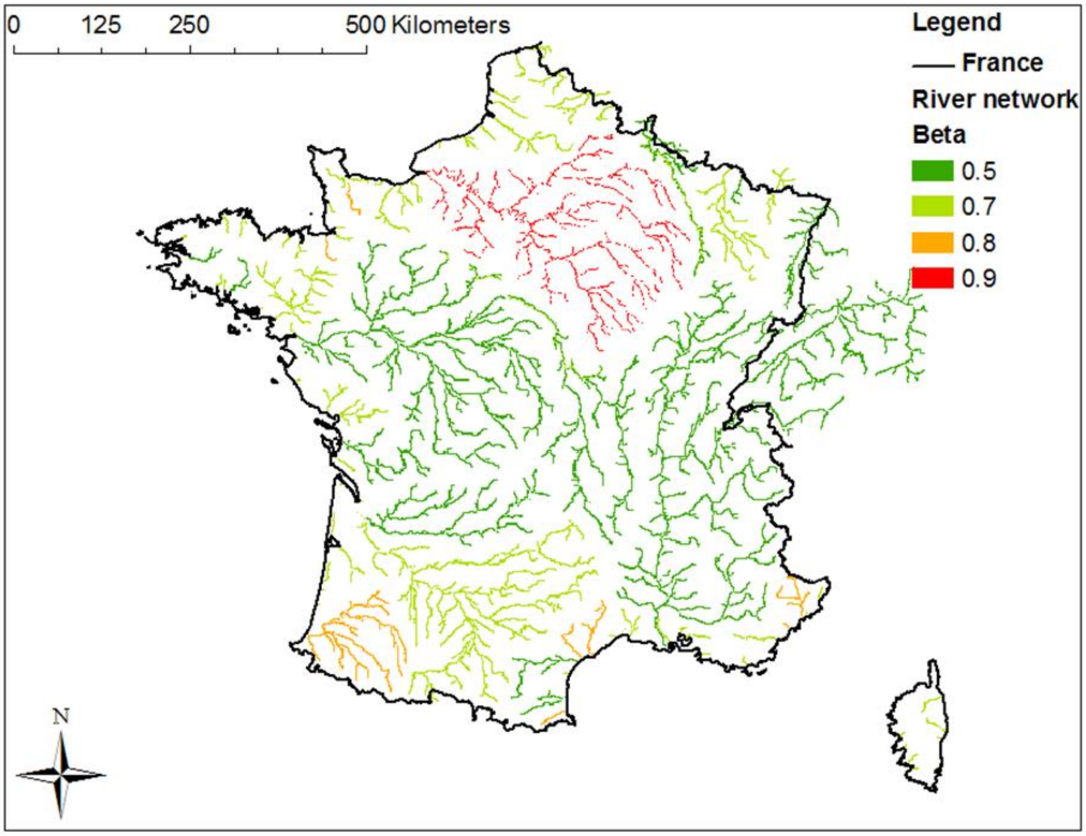

Figure 4 Map of the parameter β used for river routing in MODCOU within SIM-France

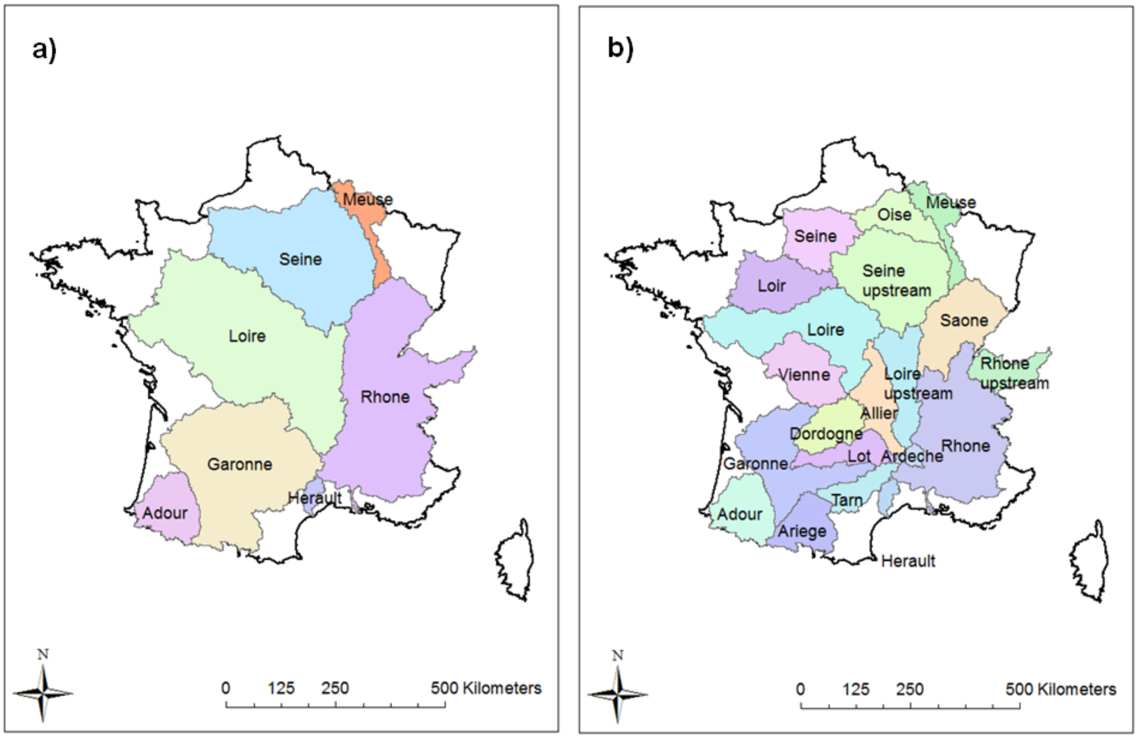

Figure 5 Basins treated independently during optimization of RAPID parameters in SIM-France. a) Seven major river basins. b) Twenty sub-basins

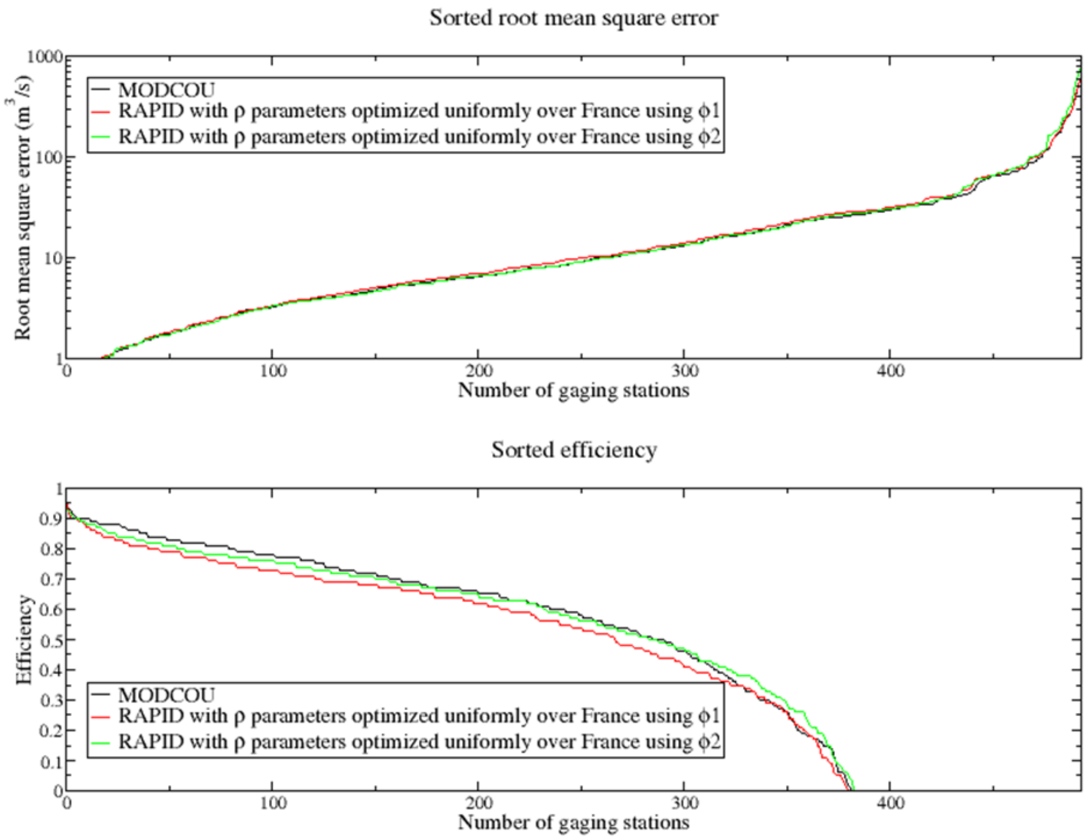

Figure 6 Comparison of sorted RMSEs and efficiencies for the year 1995-1996 between MODCOU and RAPID with ρ parameters optimized uniformly over France using the original cost function ϕ_1 and using the new cost function ϕ_2

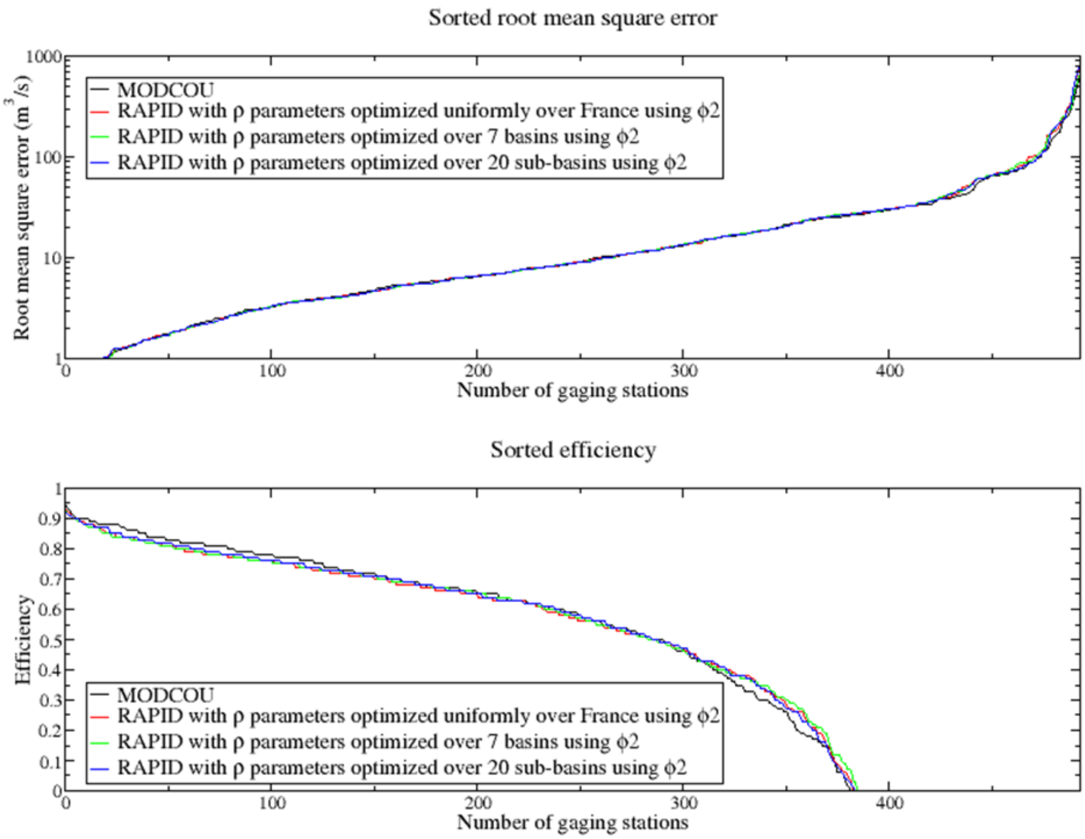

Figure 7 Effect of sub-basin optimization for RAPID on RMSEs and efficiencies for the year 1995-1996 with ρ parameters using the new cost function ϕ_2

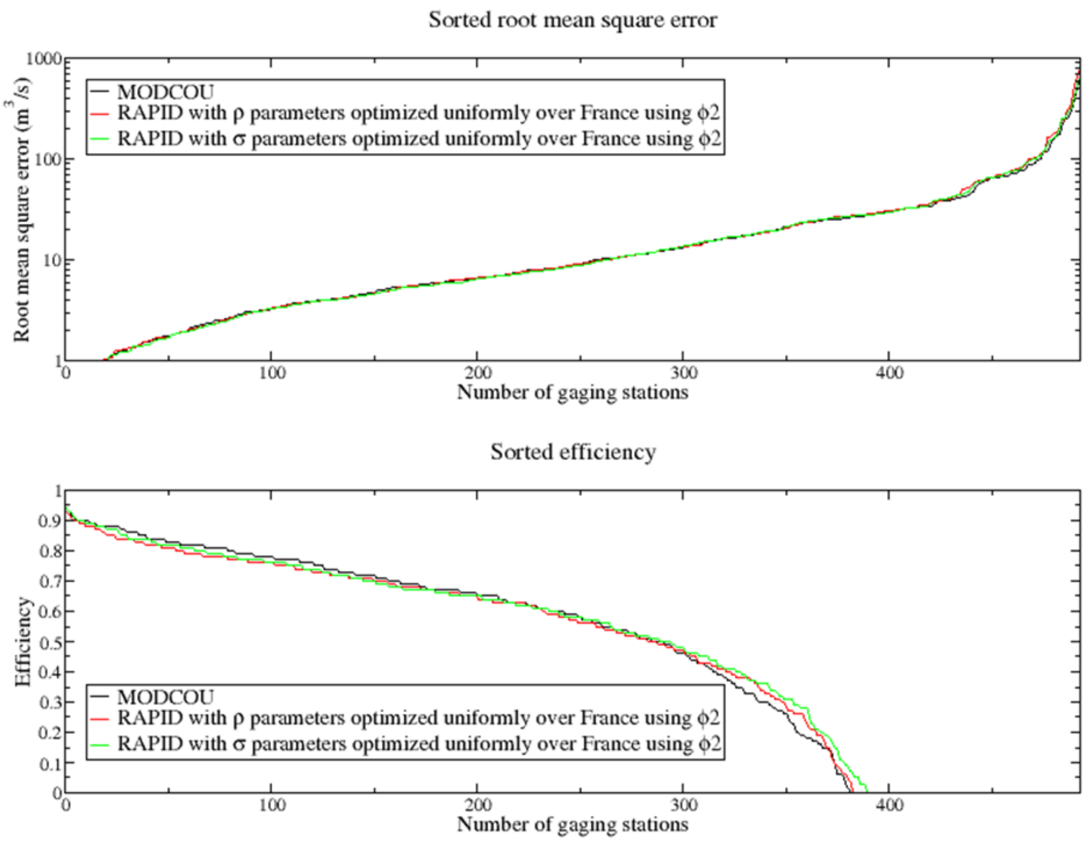

Figure 8 Effect of set of parameters ρ and σ for RAPID on RMSEs and efficiencies for the year 1995-1996 using the new cost function ϕ_2 uniformly over France

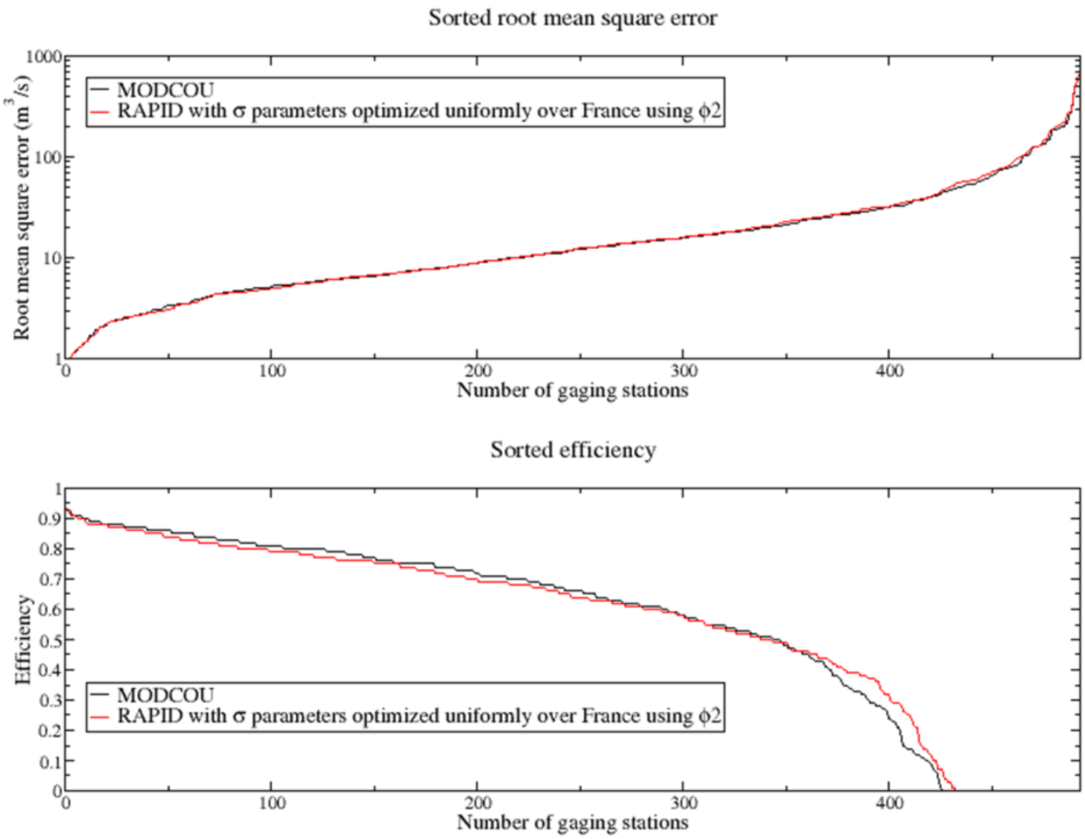

Figure 9 Comparison of sorted RMSEs and efficiencies for the years 1995-2005 between MODCOU and RAPID with σ parameters optimized uniformly over France using the new cost function ϕ_2

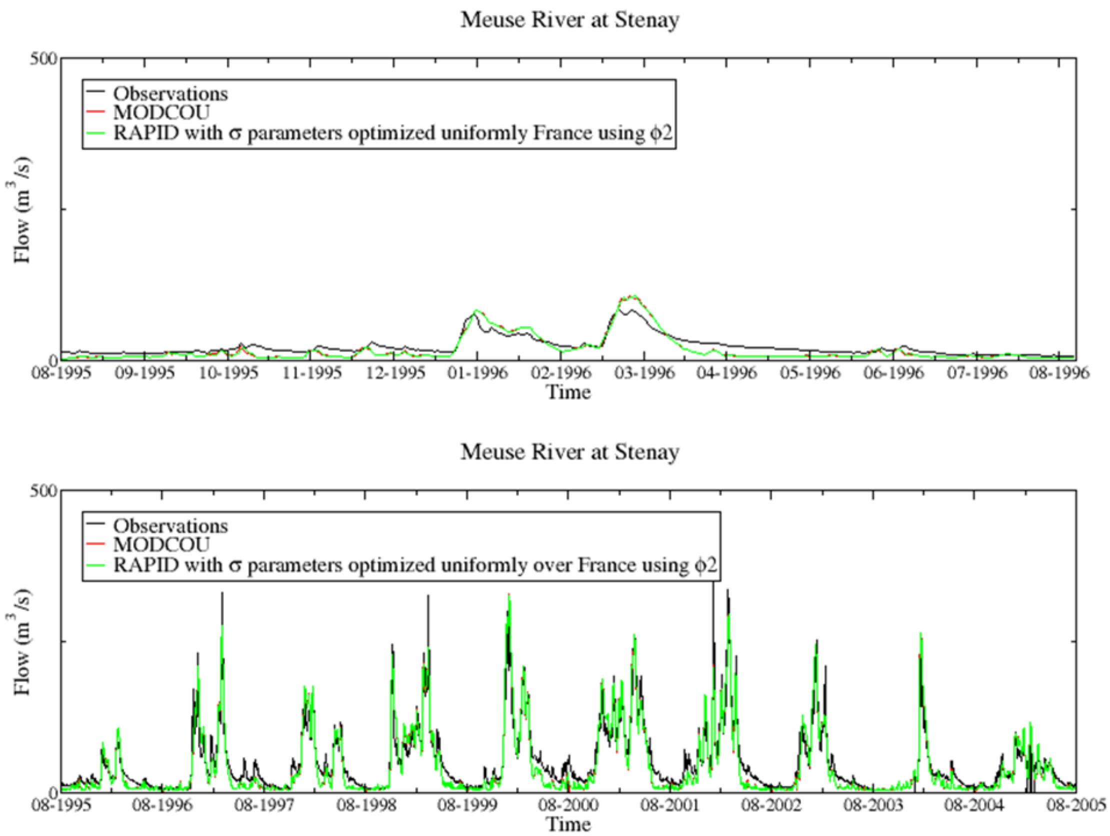

Figure 10 Comparison of 1995-1996 and 1995-2005 hydrographs for the Meuse River at Stenay obtained by MODCOU and RAPID with σ parameters optimized uniformly over France using the new cost function ϕ_2

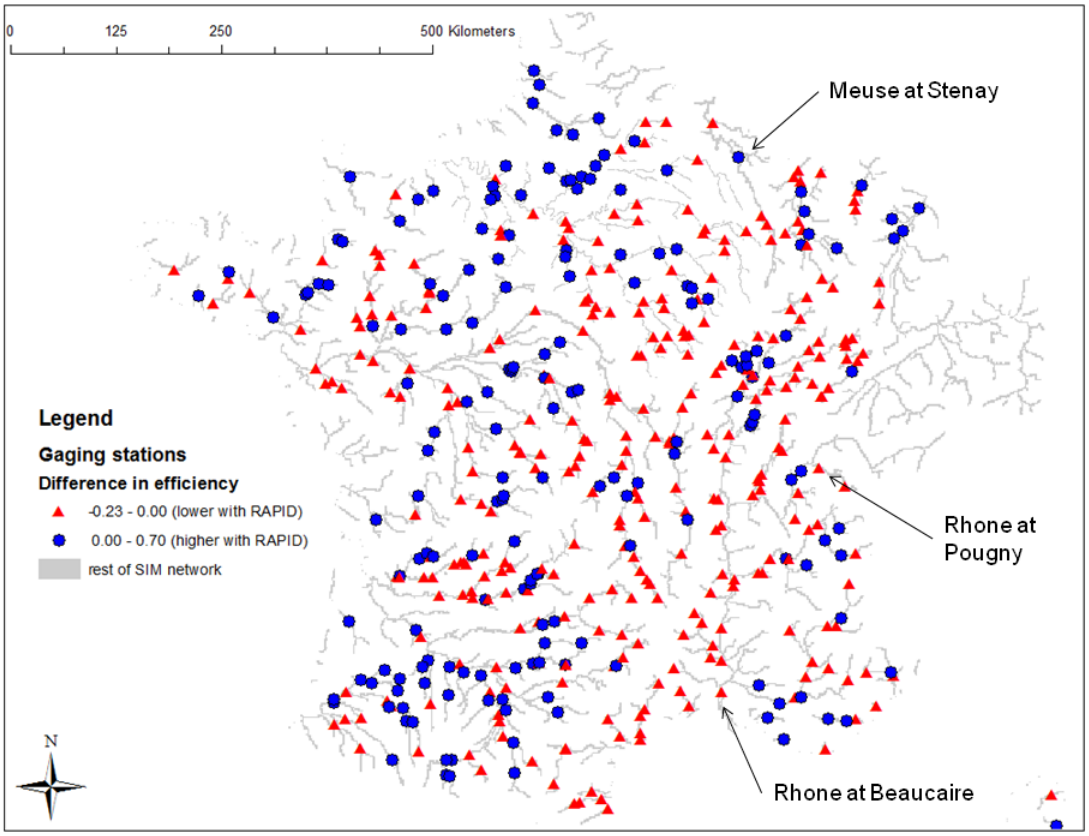

Figure 11 Spatial difference of efficiencies obtained for the years 1995-2005 between RAPID using σ parameters optimized uniformly over France using the new cost function ϕ_2 and MODCOU

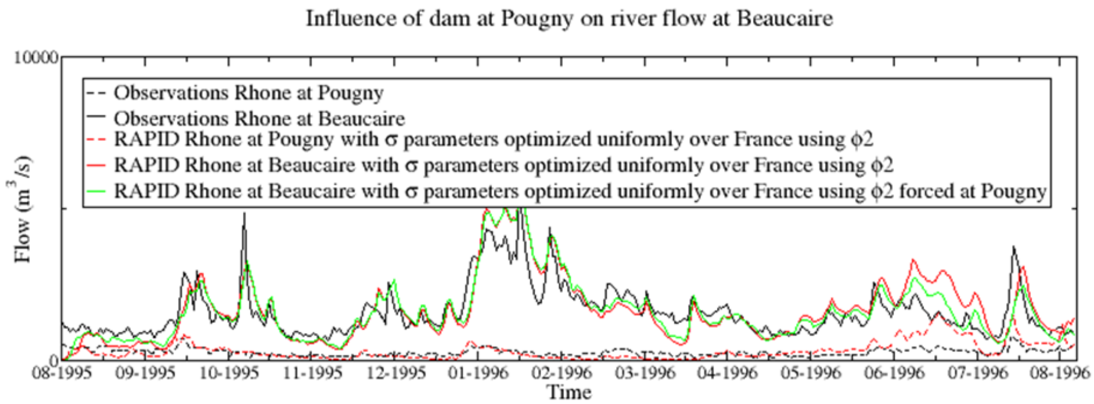

Figure 12 Comparison of RAPID discharge calculation at the outlet of the Rhône River (at Beaucaire) with and without forcing at the outlet of Lake Geneva (at Pougny).